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ROTATING GALACTIC ARMS AND LEADING-EDGE SHOCK WAVES IN H II

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ABSTRACT

A magnetogasdynamic theory of galaxies is presented. The theory provides an energy source for the coronal heating called for in theories of Pikelner and Spitzer. The magnitude of the energy source can be calculated and appears adequate for Spitzer's theory and possibly for that of Pikelner. In order to agree with other aspects of our knowledge of spiral galaxies, bar spirals in particular, it is necessary to assume that spiral arms are shaped by supersonic drag with attendant shocks. The angular motion of the galaxy produces a flow pattern in H II gas such that the flow is subsonic within a certain distance from the galactic center and is supersonic outside it. We are thus led to what might be called the Sonic Circle Theory of galactic structure. The "sonic circle" coincides, in the case of a barred spiral, with the extremities of the bar. The paper discusses, with the sonic circle theory, various aspects of normal and barred spirals including our own galaxy.

I. INTRODUCTION

Although much work has been done and continues to be done in an attempt to explain galactic structure, almost all basic questions pertaining to galactic structure remain unsolved. To the best of the author's knowledge there are still no generally accepted explanations as to why (a) a spiral galaxy rotates with arms trailing, (b) the tips of some bars are kinked, some not, and (c) some spirals are barred, some not. In the present paper we shall attempt to devise a magnetohydrodynamic theory that seems to provide possible answers to questions of the kind just mentioned and furthermore allows us to calculate certain quantities that can be checked against their values obtained independently from other theories.

We are mainly concerned with the galactic theories of Spitzer (1956), Pikelner (1958), and those contained in the review articles of van de Hulst (1958), and of Parker (1958), and the work of several other authors, to be mentioned later, who have contributed to our knowledge of the magnetic fields, the structure, and the kinematics of galaxies. In all these speculations beyond the reach of simple observation it is necessary to rely on a very broad field of astronomical endeavor ranging through measurement of the polarization of starlight, measurement of cosmic rays, and radio and optical astronomy.

For brevity we shall refer to our new theory as the Sonic Circle Theory of Galactic Structure, hereafter referred to as the SC theory. In the SC theory a spiral galaxy is envisioned as consisting of plasma-magnetic arms, spiral shaped, and in rigid body rotation, in a medium which consists principally of a contimuum of H II gas but also includes less importantly stars and clouds of H I. The hallmark of the SC theory is the sonic circle outside of which the motion of the galactic arms in H II gas would be impeded by supersonic drag; inside, the subsonic drag would be comparatively slight. The radical difference between the character of subsonic and supersonic flow provides a natural alternative separating the two branches of the Hubble classification of either normal spirals or bar spirals: normal spirals will have the sonic circle inside the nucleus while barred spirals will have the sonic circle outside the nucleus and, furthermore, the tip of the bar will coincide with the sonic circle.

The ability, no matter how satisfying, of a galactic structure theory to provide plausible explanations matching the observed varieties, needs to be supported by some quantitative checks of the suggested mechanisms. Fortunately, we find in the literature two theories concerning galaxies which lead to certain quantitative results in common with some from the SC theory. We consider these quantitative checks, early, because of their importance, and practical independence of other detailed features. The over-all plan is, by section:

II. QUANTITATIVE VERIFICATIONS; III. PRACTICAL GALAXY MODEL, presented are data from the literature to support Section II; IV. BASIC IDEA, the SC theory is formally introduced; V. ROOT BENDING QUESTION, an interesting aspect of the SC theory is considered in detail; VI. THE HUBBLE CLASSIFICATION AND THE SC THEORY.

II. QUANTITATIVE VERIFICATIONS

In this section we use many numerical values pertaining to galaxies but defer reference to the source material until the next section, III.

a) Coronal Temperature

The galactic arms are known to rotate and the arms trail. Furthermore, the material speeds, of the order 220 km sec^{-1} in our own galaxy (van de Hulst, H. C., 1958, p. 915) are known to exceed the speed of sound in H II gas, 19 km sec^{-1} (Kaplan, S. A., 1958, p. 62). We infer that the arms may be producing shocks in the H II medium. Can the shocks produce temperatures corresponding to that believed to exist by Spitzer (1956) in the galactic corona? To investigate this question we estimate the temperature rise of H II through the shock. The pressure of H II ahead of the shock is known since we have n_1 and T_1, the particle density and temperature, respectively, of the corona in and near the disc; the pressure p_2 behind the shock we take as the same order as the magnetic pressure in an arm. Figure 1 ([redacted]) shows how we envision the problem. Strong shock theory (Kaplan, 1958, p. 66) gives the following formula for the temperature ratio

$$\frac{T_2}{T_1} = \frac{1}{4}\frac{p_2}{p_1}$$

with $n_1 = 10^{-1}$ cm^{-3}, $k = 1.38 \times 10^{-16}$ erg ^oK, $T_1 = 10^4$ ^oK, and $p_1 = 1.38 \times 10^{-13}$ dyne cm^{-2}. Therefore, if we take p_2 equal to the arm magnetic pressure corresponding to $H = 3 \times 10^{-5}$ gauss, we have, using $p = H^2/8\pi$ where p is pressure dyne cm^{-2} and H is field intensity in gauss, $p_2 \cong 3.6 \times 10^{-11}$ dyne cm^{-2}. The equation for the temperature ratio now gives $T_2/T_1 \cong 0.7 \times 10^2$. **Therefore, since**

$T_1 \cong 10^4$ °K the shocks might be capable of producing the 10^6 °K temperature in the corona called for in the Spitzer theory, for, while we cannot trace the shock details into the high corona, the temperature $\sim 10^6$ °K prevails even close to the disk, hence near where our calculation applies. The Pikelner theory does not have such a severe temperature requirement, only 10^4 °K.

b) Coronal Energy Source

The energy sources for maintaining the temperatures of the Pikelner (1958) and Spitzer (1956) coronas have never been established. In the case of the Pikelner halo, the dissipation is such that Pikelner (1958, p. 936) has to seek the source in the galactic nucleus. On the other hand, Spitzer (1956, p. 31-32) mentions several possible heating mechanisms, one of which postulates shock waves produced by moving gas clouds as a possible heating mechanism; in this connection, we take the view that a spiral arm could qualify as a moving gas cloud. In the case of the Pikelner halo, shocks are considered the heating source but there is no known driving mechanism for them, of the strength required, outside of the galactic nucleus.

Can the shocks produced by the moving galactic arms qualify as the energy source? Consider the work per second done by the arm magnetic tension on the portion of the arm farther from the galactic center than our sun. This is, per arm, $pAV \cos \alpha$ where p is the magnetic tension in the arm, A is arm cross-sectional area, and V is our sun's peripheral speed. In an order of magnitude calculation, the spiral angle α of the arm will be neglected, especially since the arms of most galaxies tend to be tightly wound. The pressure p has been already computed as p_2 in the previous calculation, therefore, $p = 3.6 \times 10^{-11}$ dyne cm^{-2}. If the arm thickness is 250 pc and three times that wide, we have $A = 1.8 \times 10^{42}$ cm^2. We then have for the power output of two arms $2pAV \cos \alpha = 2.8 \times 10^{39}$ erg sec^{-1}.

The dissipations required by Spitzer and Pikelner are shown in Figure 2.

We see that the energy supply is capable of driving shocks that could heat the Spitzer corona.

This should not be interpreted as meaning that the Spitzer model is necessarily favored by the present calculation. We could easily be low by a considerable amount in our estimates of the arm rotational speed which, in the SC theory, may be quite different from the general galactic material rotational speed. The reason is that the arms in our view move through the galactic medium just as the shocks do. In this process, considerable rotational motion is likely to be imparted to the galactic medium outside the arms, and it could be this motion that accounts for most of the galactic rotation that we measure while the rotational speed of the shocks and arms may be still considerably higher. Thus, the Pikelner energy supply could conceivably be attained but it would be necessary to assume Mach numbers of the order of 100 in order to get sufficient increase in V.

The foregoing energy supply calculation neglects the energy supplied by the outflow of gas along the galactic arm. If a rotating jet of gas in a stationary gaseous medium be considered we see that the rotary motion of the jet can under certain conditions give rise to shocks just as any rotating solid body can and hence the outflow along the rotating arm can contribute to the coronal heating just as an arm with no outflow can. (The arm with no outflow can be likened to a whirling rope, for which there would be no outflow, which takes up a spiral shape due to drag and provides a heating effect.) In our calculation we considered only the case without outflow along the arm. The important thing, however, is that we erred on the low side by neglecting the outflow in calculating our energy supply.

c) Energy That Goes Into Drag

In the preceding calculation, we found that the work done on the galactic arm by the magnetic tension was sufficient for coronal heating but we still would like to verify that this energy could go in turn into drag and so heat. Let us consider the Newtonian approximation for hypersonic drag to test whether the drag could be high enough to absorb the energy put into the arm. The drag of a body of thickness t, length b, such that the frontal area presented to the stream is tb, with proton density n, and velocity V, will be $nmtbV^2$ for nonspecular reflection and where m is the proton mass. Then for two arms we have the power absorbed by drag

$$\text{Energy sec}^{-1} = (2)nmtbV^3$$

We take $t = 250$ pc for the galactic arm thickness; we let b equal the difference in radii of innermost and outermost arm distances, about 5×10^3 pc; $n = 0.1$ cm^{-3}; $V = 220$ km/sec. The result is

$$\text{Energy sec}^{-1} \cong 3.5 \times 10^{40}$$

which is again entirely adequate for the Spitzer theory and, since the arm speed could be much greater than the material speed, this figure could again be adequate for the Pikelner theory too.

It appears, in concluding this section, that associating galactic arms with shocks leads to results that are compatible with those from existing theories of galactic structure.

III. PRACTICAL GALAXY MODEL

The following description of a spiral galaxy is believed to be representative for the purposes of order of magnitude calculations. Numerical values are shown in figure 2.

The galactic halo or corona is, in Spitzer's theory (1956), at a temperature of $\sim 10^6$ °K. This constant temperature prevails throughout a spherical volume with diameter roughly as large as the galaxy itself.

In and near the disk, the temperature must have the more familiar intersteller H II value 10^4 °K (Spitzer, p. 7, 1954). We still have, however, pressure equilibrium between H I and H II regions and therefore, since we have 10 H atoms cm^{-3} and 100° K in the normal H I cloud, the density in and near the disk would be the usual intersteller value 10^{-1} electrons or protons cm^{-3}. These figures, 10^4 °K and 10^{-1} cm^{-3}

for temperature and density, are in line with those of Parker (1958, p. 960). The Pikelner (1958, p. 937, section 5) corona is cooler, 10^4 °K throughout with about the same particle density (Pikelner 1958, p. 936, end of section 3) we ascribed to the Spitzer model in the disk vicinity.

The magnetic field intensity in the corona is about on order of magnitude less than that in the galactic arm. The arm value is the order (Parker 1958, p. 957, A) 10^{-5} gauss with 3×10^{-5} gauss (Woltjer 1962, p. 166) tending to become accepted in the most recent literature, although this value was not regarded as unreasonably high previously. The coronal value would then become 3×10^{-6} gauss which corresponds also to the pressure of a gas under the conditions which we have adopted for the coronal gas in and near the disk.

Some recent quotations on magnetic fields are given by Sciama (1962, p. 317-25): spiral arms, 5×10^{-6}; disk, 2×10^{-6}; halo, 10^{-6}; intergalactic space, 5×10^{-7} gauss. (However, the value for the arm seems low, for reasons given by Woltjer (1962, p. 167).)

Furthermore, Biermann and Davis (1960, Abstract) deduce 2×10^{-5} gauss for the average disk value while the values in the arms themselves should be higher. See also Elvius and Herlofson (1960, p. 307) who consider arm values $1 - 5 \times 10^{-5}$ gauss.

For later use we also need some kinematical and geometrical information on galaxies. The thickness of a galactic arm is taken as 250 pc (van de Hulst 1958, p. 922, Tab. IV) and the width as three times this.

The angular velocity of an arm of our own galaxy is presumed to be given with sufficient accuracy by the ratio of the sun's peripheral speed, about 220 km sec^{-1} to the sun's distance from the galactic center about 8.2×10^3 pc.

The Spitzer corona dissipates energy by radiation with the power (Spitzer 1956, p. 31) 1.2×10^{39} erg sec^{-1}; the corresponding number for the Pikelner corona is (Pickelner 1958, p. 936, section 4) 3×10^{41} erg sec^{-1} which Pikelner states to be greater than any known power supply outside of the galactic nucleus.

IV: BASIC IDEA

In the preceding section, the point of view was taken that the galactic arms were phenomena of high speed aerodynamics and attention was focused on the quantitative checks to which such a view could be subjected. We shall now take the straightforward approach. The basic idea is that the rotating arms, or bar, or disc, of the various galactic systems will at some radius from the galactic center exceed the speed of sound (in H II gas) and, outboard of this radius, shocks will form ahead of the arms and bend the arms backward in a spiral pattern. This idea implies several subordinate ideas (a) the H II gas forms a continuum (as a comparatively resting background), (b) the arms are somehow like solid bodies rotating through the H II medium, (c) the arms actually exceed the speed of sound in H II, (d) we can neglect the ensnaring, as it were, effect of the background field lines on the arms which would cause a "magnetic drag". We now consider these separately: (a) Our view on this is as stated by E. N. Parker (Parker 1958, p. 960, p. 965). Most of interstellar space is pervaded by tenuous H II gas at 10^4 °K (with 10^6 °K called for in some theories) with H I relatively dense in clouds. (b) The arms are considered to be plasma-magnetic structures and since the H II plasma is infinitely conducting the magnetic fields are frozen into the arm H II whereas H II already external to the arm remains external. Therefore, the moving arms will act like solid bodies in the H II. (c) The speed of sound in H II at 10,000 °K is 19 km sec^{-1}. (Kaplan 1959, p. 20) The speed of our sun is an order of magnitude faster, however. Therefore~~, there is~~ no question that the arms can have supersonic velocities at some distance from the nucleus. (d) We assume there is no large scale drag-effect, of the disc magnetic field external to the arms, on the basis that : (1) the kinetic energy of the flow past the arms is about three orders of magnitude greater than the magnetic energy; (2) there are no indications that the magnetic fields in the halo, nor disc are especially likely to retard the arms, as if there were a large scale field perpindicular to the disc; (3) there may be other factors working to prevent the background field from significantly braking the arms such as the magnetic geometry, or the likelihood that the observed magnetic fields are localized in the H I clouds with significantly weaker fields in the H II continuum.

We now consider the question of the arm motion becoming supersonic at some radius. A disturbance describing, at constant angular rate ω, a circle of some unspecified diameter in a gas will, in the small disturbance approximation, produce phenomena governed by the wave equation

$$\frac{1}{a^2} \varphi_{tt} = \varphi_{rr} + \frac{1}{r} \varphi_r + \frac{1}{r^2} \varphi_{\alpha\alpha} + \varphi_{zz} \qquad (1)$$

written for a potential φ in cylindrical coordinates fixed in a medium with sound speed a. These coordinates are an inertial frame with the circle described by the disturbance as $r = \text{const}$ in the plane $z = o$. We now consider what happens when (1) is transformed to coordinates which rotate with the disturbance. In the new coordinates r, θ, z, the flow is steady, while the transformation is simply $z = z$, $\theta = \alpha + \omega t$, $r = r$. Equation (1) now becomes in the rotating system

$$\varphi_{zz} + \varphi_{rr} + \frac{1}{r} \varphi_r + \frac{1}{r^2} \varphi_{\theta\theta} \left(1 - \frac{\omega^2 r^2}{a^2}\right) = 0 \qquad (2)$$

which equation indicates an essential change in local flow character (Webster, p. 239-41) on a cylinder, concentric with z, defined by

$$1 - \frac{\omega^2 r^2}{a^2} = 0$$

or, at the radius where the velocity ωr of the coordinates rigidly co-rotating with the disturbance, is just sonic. Inside the "sonic cylinder" $\omega r = a$ (Busemann 1938, 1953) (Davidson 1953) the flow is essentially subsonic. If the disturbance is inside, no waves are created; if the disturbance is outside, waves are created but reflected at the sonic cylinder. The wave pattern appears in figure 3 for a disturbance moving on a circle with $R = \omega/a$. An example of this kind of wave propagation is given in plate I for motion in a shallow water tank of (a) a point disturbance and (b) a radially directed and submerged rod. Unfortunately, the actual surface wave phenomena are not as simple as for completely submerged (in a gas) phenomena so that the wave systems are somewhat more complicated than indicated by equation (2). Nevertheless, the photograph illustrates the main features of our discussion for it shows how the waves start on the rod at a certain radius and how the waves from the point disturbance do not propagate inside of that same radius.

Transferring the foregoing ideas over to galaxies we find an explanation of a bar spiral (see figure 4a): the bar extends out to the sonic cylinder. Inside the sonic cylinder, the arm would experience only subsonic drag and would not be swept back. Outside, the supersonic drag would sweep the arm back.

Normal spirals would be explained by supposing the sonic cylinder to have a radius smaller than the nucleus, (figure 4b).

The picture that we have attempted to build up is summarized in fugure 2. Shown are the nucleus and two arms of a normal spiral galaxy with the arms rotating behind bow shock waves.

We now consider some questions that often arise in the literature on galaxies and see how they would be answered in the present theory:

(a) Why are some spirals barred, some not barred? Because the barred spiral arm and moreover actually maintained their own rotation. The shape that they took is sketched in figure 5. The motion maintained by the water flowing outward in the tubes is the angular motion labelled ω in the figure and which of course corresponds to galactic rotation. This rotation is caused by the force $\bar{F}$ which is due to fluid reaction, in the kink of the arm, that involves restriction by the kink, change of direction of momentum, and irreversible effects there, all of which can be present in the galactic counterpart. It would seem therefore that there is no need to ask why the arm does not fail at the root because the arm may actually be helping the rotation. This, of course, raises the question whether the arms can cause the nucleus to rotate, however, we do not consider the matter in this paper. In addition to maintaining the angular motion, the force $\bar{F}$ in the experiment also caused the tube to demonstrate another puzzling feature of barred spirals, namely, the straightness of the bar between the hub (nucleus) and the kink or tip of the bar. The outward component of the force $\bar{F}$ proves very effective in maintaining the bar comparatively straight against the drag of the water and the friction of the central pipe that had to rotate with the tube. A sequence from a motion picture of the experiment is shown in Plate II. One sees the shallow water tank with a barred spiral arm tube in motion in the water. The vertical column is an aluminum pipe which rotates with the arm tube and serves to feed the water that flows outward through the tube. Water is introduced at the top of the aluminum pipe (out of the picture).

The experimental setup is shown in plate III. The arm-simulating-tube rotates immersed in the circular tank. The aluminum pipe, which rotates as mentioned above, and through which water can be introduced into the arm tube has a tee at the bottom end to which the arm tube is fastened and the whole pipe assembly is supported on a thrust bearing located where the technician is pointing.

VI. THE HUBBLE CLASSIFICATION AND THE SC THEORY

It is believed that the reader will find little difficulty in explaining, with the present theory, the various spiral configurations in the Hubble classification. For instance, SBc could be a new set of arms that have not yet been bent back very far so that the kink is not pronounced. An SBb could be a late bar spiral in which the kinking process is very advanced and the arms with little outflow have been pushed well back; the tube experiment represented SBb well. The SBa could then be an advanced state of SBb where the arms trail in a circle. We mention these explanations only in the interest of making the implications of the present theory more clear with the realization that other explanations for the Hubble classification already exist.

The normal spirals appeal to differ mainly in the tightness of winding. We have not mentioned that differential rotation also plays a role in the present theory in that it distorts the Mach waves that are shown in figure 3. When there is considerable differential rotation of the H II medium, it can be shown that the Mach waves are more tightly wound. This means that differential rotation will cause the bow shock waves, behind which the arms advance, to be more tightly wound. Thus we see that the various normal spirals in the Hubble classification could be just manifestations of various states of differential rotation. Assuming the differential rotation increases with galactic age, and since differential rotation causes the shocks (hence, the arms) to be more tightly wound, we see that Sc would be early and Sa would be late.

Before closing, let us examine the tight-winding phenomenon in more detail. Suppose first there is not differential rotation, we can then have, see figure 6 (a) (for a disturbance moving in a circle of radius r, at angular velocity ω, and making a Mach wave at angle α with speed of sound a) the relation $\sin \alpha = a/r\omega$. At the sonic circle r_s we have $r_s \omega = a$, so a/ω can be eliminated, leaving $\sin \alpha = r_s/r$ which may be written in a form convenient for subsequent comparison

$$\frac{r - r_s}{r_s} = \frac{1}{\sin \alpha} - 1$$

This equation gives in terms of the sonic radius r_s, the radius r to a point on a Mach wave where the Mach angle is α.

Now suppose differential rotation is present of amount $v(r) =$ constant. The velocity diagram is as in figure 6b. We have $\sin \alpha = a/(r\omega - v)$. At the sonic circle, the difference between wave and medium speed is a, which means $r_s\omega - v = a$. These equations lead to

$$\frac{r - r_s}{r_s} = \frac{1}{1 + \frac{v}{a}} \left(\frac{1}{\sin \alpha} - 1 \right)$$

This equation shows us how the radius where α has a certain value is contracted according to the value of v. Since v can be considerably greater than a, we see that the contraction or tight-winding can be considerable. For instance if v is only $2a$, the factor $1 / (1+v/a)$ is $1/3$.

Thanks are due to Dr. A. Busemann for his suggestion to utilise a shallow water analogy tank in this investigation.

REFERENCES

Biermann, L. and Davis, Leverett, Jr., 1960, Zeitschrift fur Astrophysik 51, 19-31.

Busemann, A. 1938, ZAMM., 18, 31-38.

Busemann, A. 1953, The Third Midwestern Conference on Fluid Mechanics, University of Minnesota, Minnesota, p. 278.

Davidson, Robert E. 1953, NACA, T.N. 2983, 5.

Davies, R. D. et. al. 1960, Nature, 187, 1088.

Elvius, A. and Herlofson, N. 1959, Ap. J. 131, 304.

Kaplan, S. A., 1958, Intersteller Gas Dynamics, (Translation, Nov. 1959) MCL-97/V, Leason Office, Tech. Inf. Center, MCLTD, Wright-Patterson AFB, Ohio.

Parker, E. N., 1958, Rev. Mod. Phys., 30.

Pikelner, S. B. and Shklovsky, I. S., 1958, Rev. Mod. Phys., 30.

van de Hulst, H. C., 1958, Rev. Mod. Phys., 30.

Sciama, D. W., 1961, M. N. Roy. Ast. Soc., 123, 317.

Spitzer, L. 1956, Ap. J. 124, 20.

______, 1954, ibid, 120, 1.

______, 1958, Rev. Mod. Phys., 30.

de Vaucouleurs, G., 1962, Astron. J. 67, No. 5, p. 270.

Webster, A. G., Partial Diff Egs of Math Phys. Hafner Publishing Company, Inc., New York, 1950.

Woltjer, L. 1962, Problems of Extra-Galactic Research, I.A.U. Symposium No. 15, August 10-12, 1961, p. 166-169. The MacMillan Company, New York.

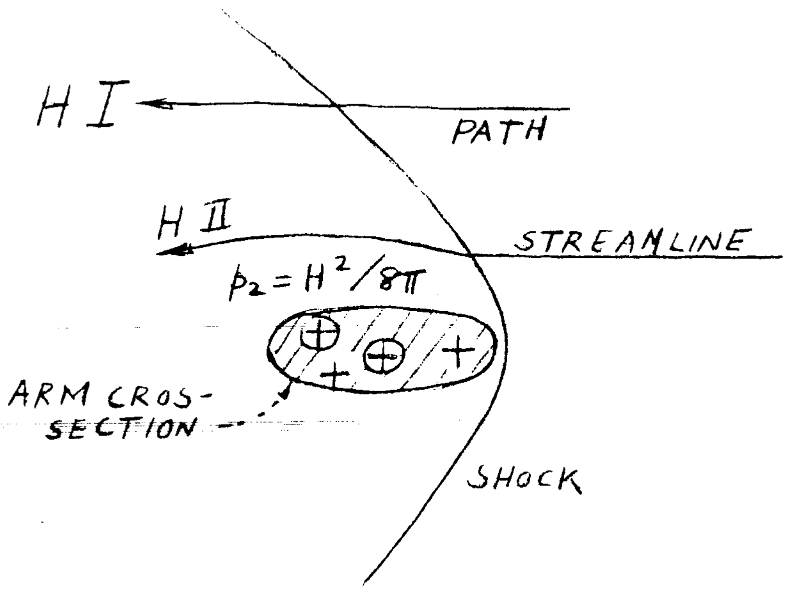


FIGURE 1. MAGNETIC PLASMA ARM AND LEADING EDGE SHOCK CONCEPT.

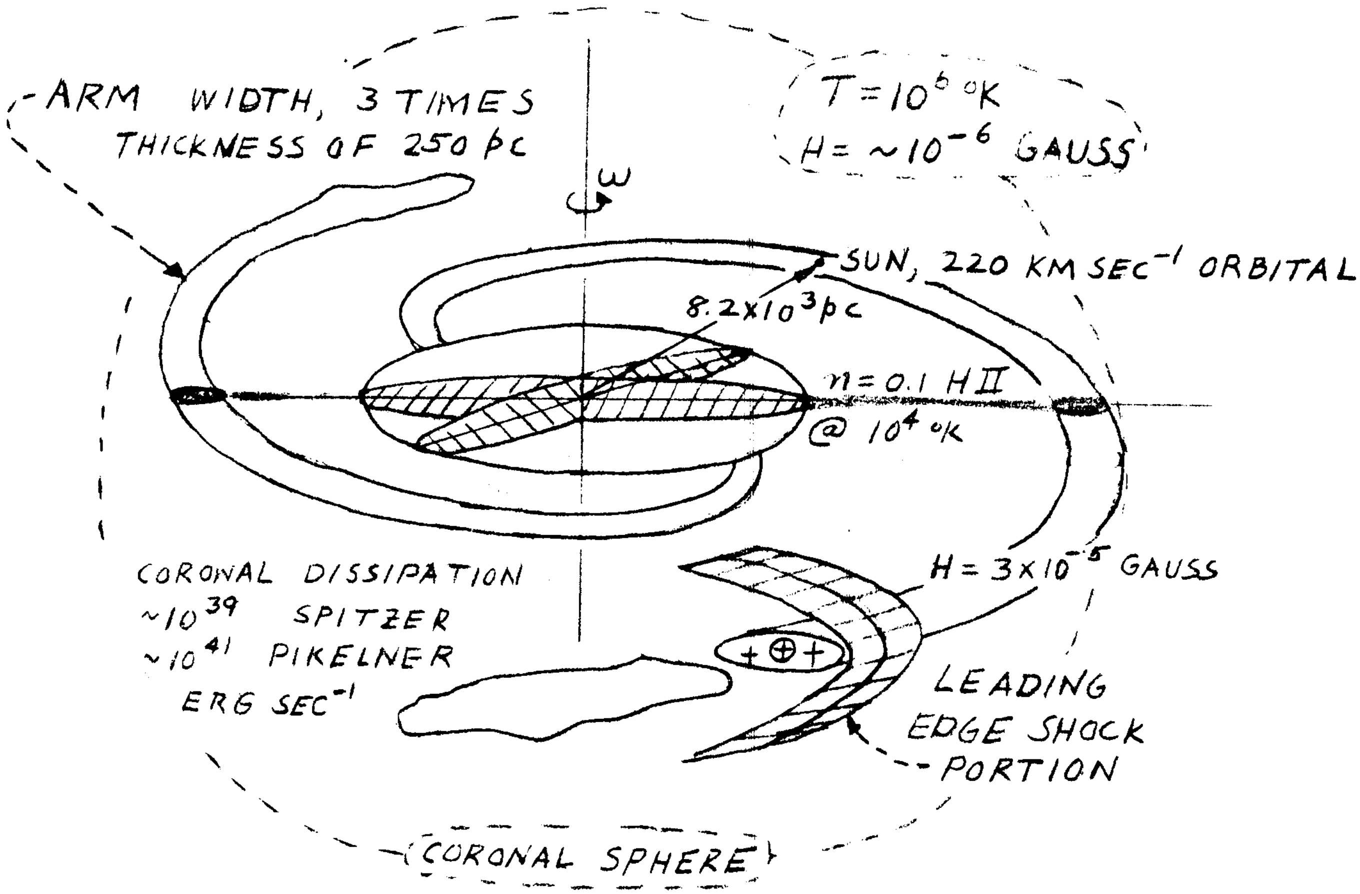


FIGURE 2. GALAXY MODEL.

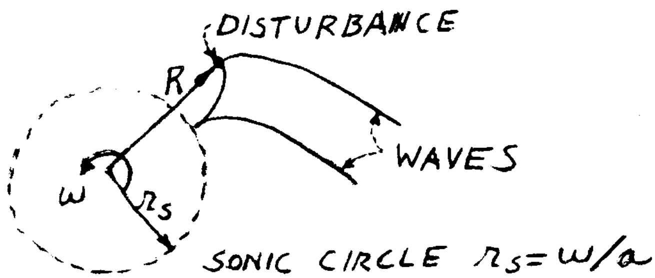
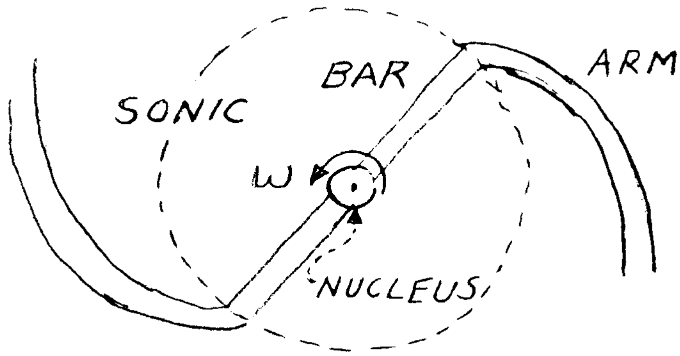


FIGURE 3. SONIC CIRCLE AND DISTURBANCE MOVING ON A RADIUS.

(a) BAR SPIRAL



(b) NORMAL SPIRAL

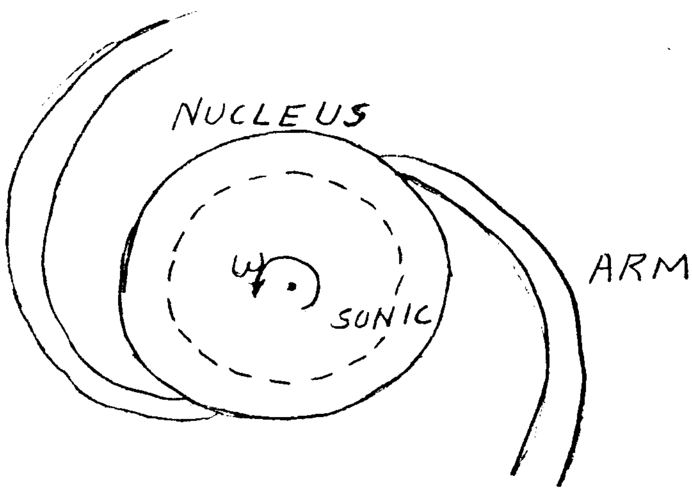


FIGURE 4. SONIC CIRCLE THEORY FOR NORMAL AND BARRED SPIRALS.

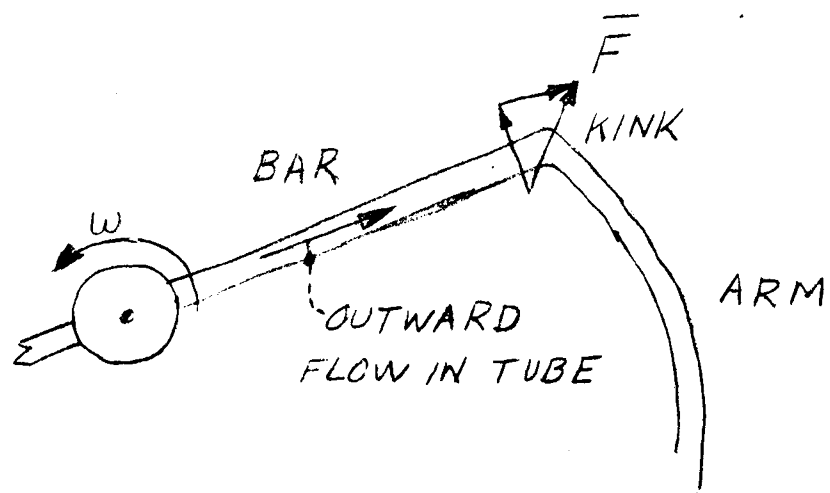


FIGURE 5. ONE ARM OF BARRED SPIRAL SIMULATOR WITH FORCE $\bar{F}$ DUE TO EFFECT OF KINK ON OUTFLOW.

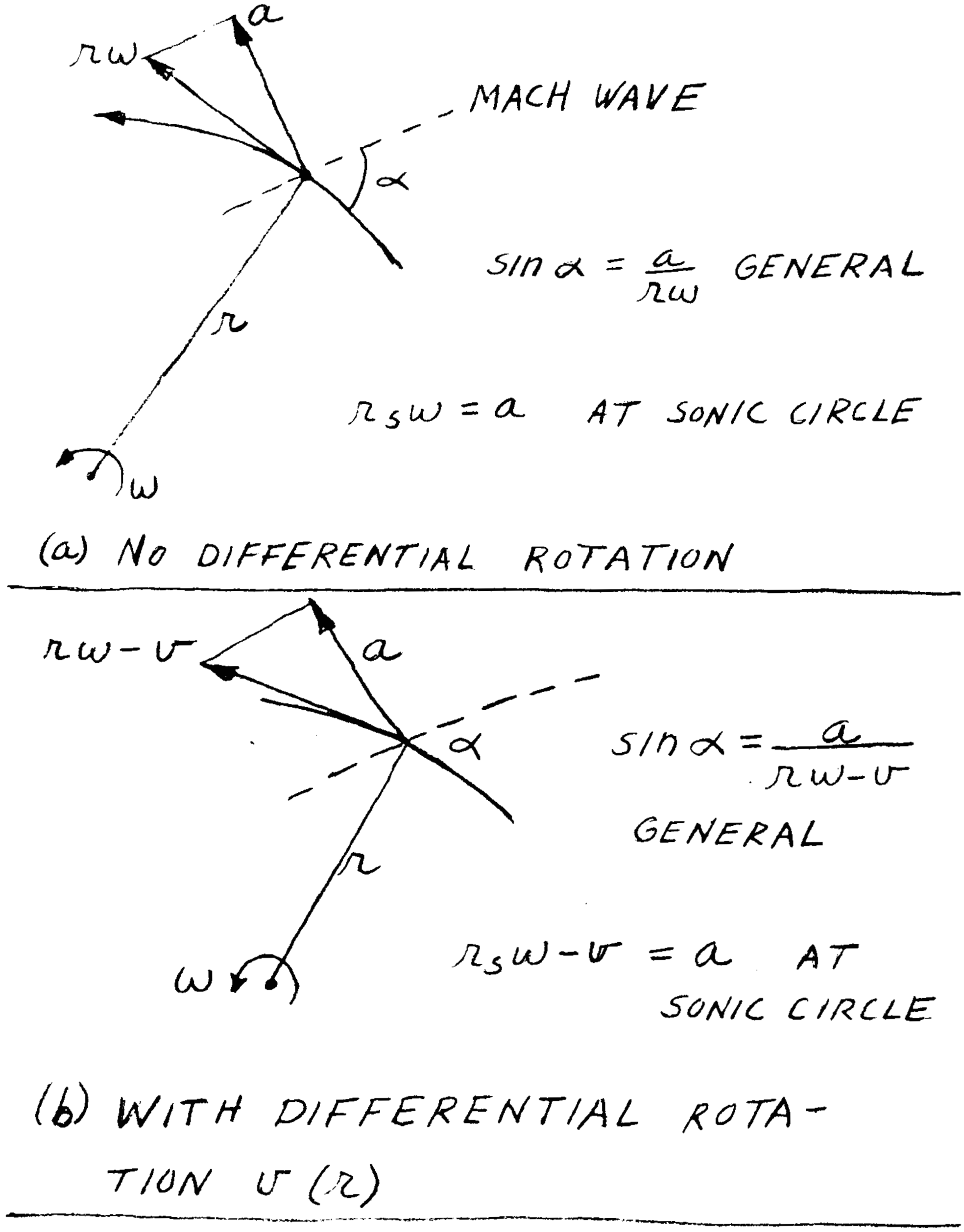


FIGURE 6. MACH WAVE GEOMETRY FOR ROTATING DISTURBANCE.

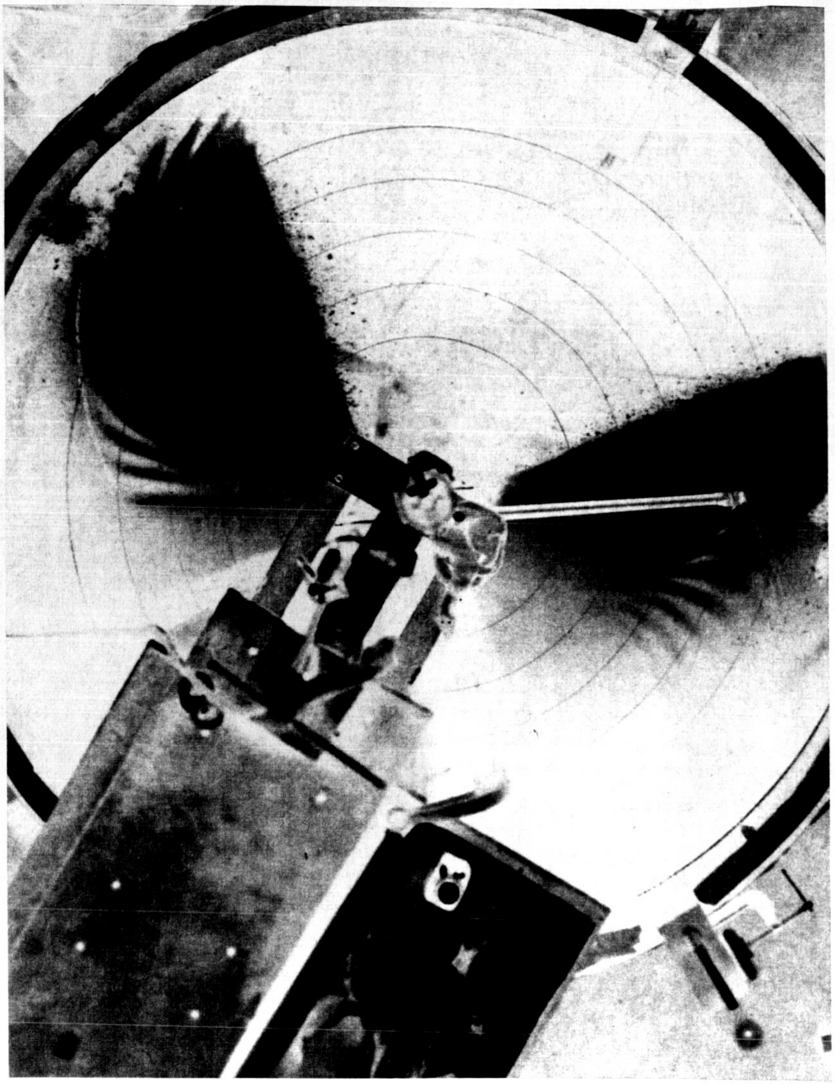
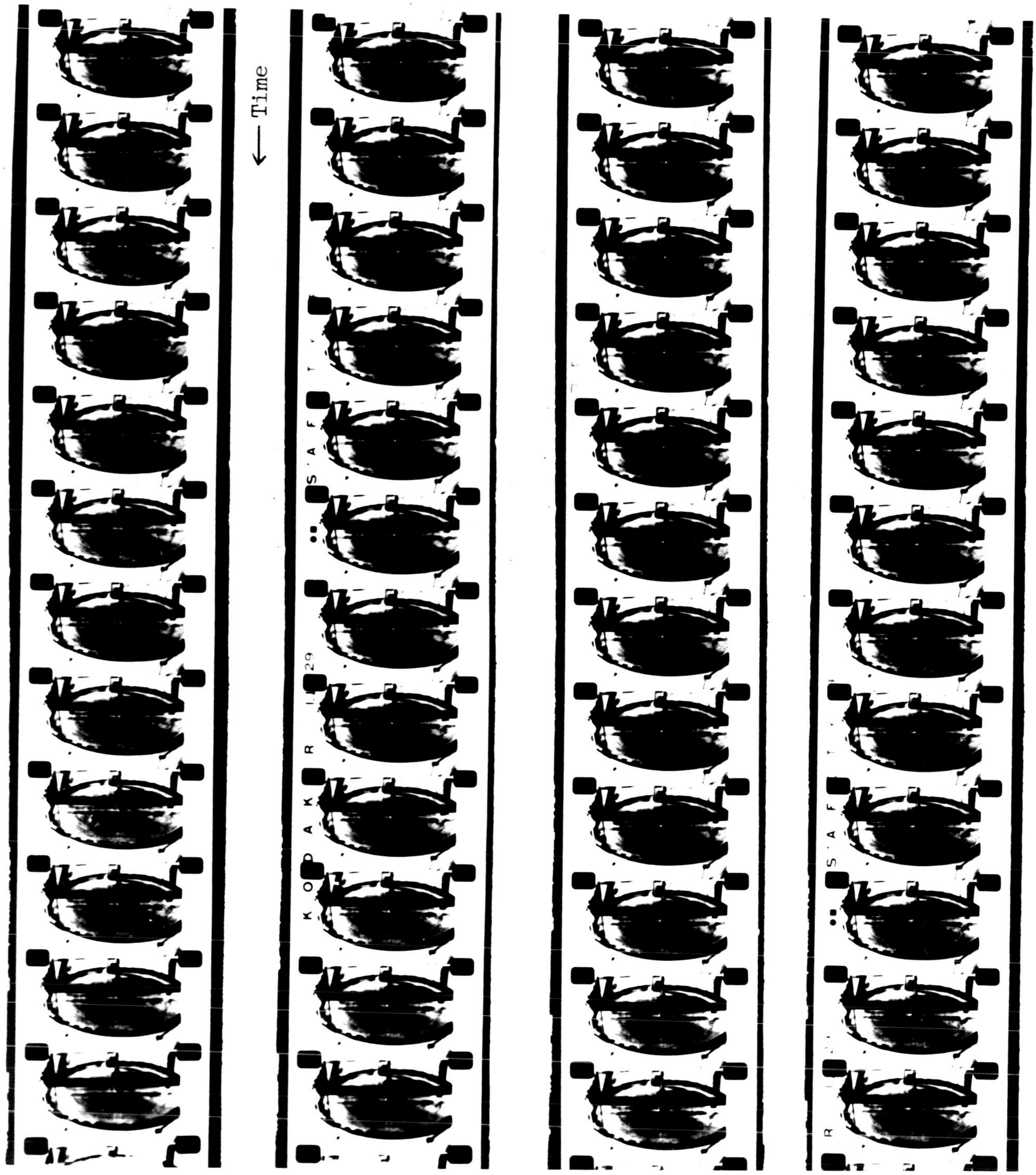


Plate I.— Shallow-water waves, made by a pointlike disturbance (right) and by an immersed rod (left).



1 2 3 4

Plate II.– Motion picture sequence of a flexible tube simulating a rotating galactic arm, see text, section V. Frame speed, 24 sec-1.

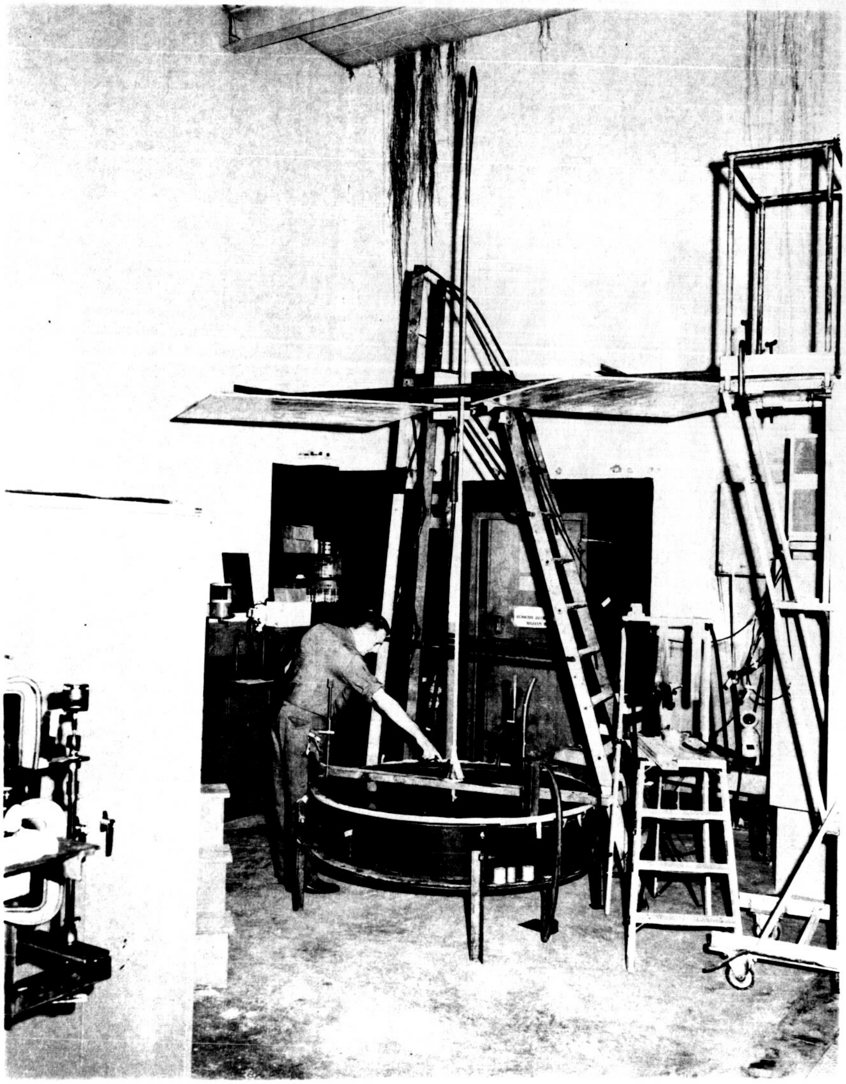


Plate III.- Galactic-analogy-tank setup.